

MEASUREMENTS OF THE MASSES, LIFETIMES AND DECAY MODES OF HADRONS AT TEVATRON

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The Tevatron provides 1.96 TeV $p\bar{p}$ collisions and allows for collection of rich b -hadron samples to the two experiments CDF and DØ. The study of heavy flavor properties represents a fruitful opportunity to investigate the flavor sector of the Standard Model (SM) and to look for hints of New Physics (NP). Here we report the first measurement of polarization amplitudes in B_s^0 charmless decays, world leading results on b -hadron lifetimes, and measurements of several other properties of b -hadrons.

1 $B_s^0 \rightarrow \phi\phi$ polarization measurement

The $B_s^0 \rightarrow \phi\phi$ decay proceeds through a $b \rightarrow s\bar{s}s$ quark level process, whose dominant diagram is the $b \rightarrow s$ penguin: it is potentially sensitive to NP that could manifest itself through the presence of new particles in the penguin loop. In addition, the $B_s^0 \rightarrow \phi\phi$ is a decay of a pseudo-scalar meson to two vector mesons whose differential decay rate is determined by three independent amplitudes corresponding to different polarizations: one longitudinal (A_0) and two transverse, with spins parallel (A_{\parallel}) or perpendicular (A_{\perp}) to each other.^a In the SM, $|A_0|^2 \gg |A_{\parallel}|^2 + |A_{\perp}|^2$ is naively expected in B decays to two light vector mesons.¹ This was experimentally confirmed by BaBar and Belle in tree-dominated transitions.² In contrast, it was found $|A_0|^2 \simeq |A_{\parallel}|^2 + |A_{\perp}|^2$ in $b \rightarrow s$ penguin decays.³ In order to shed light on this “polarization puzzle” additional experimental information is required and $b \rightarrow s$ penguins in charmless B_s^0 decays are a promising opportunity. The $B_s^0 \rightarrow \phi\phi$ decay has been observed in its $K^+K^-K^+K^-$ final state for the first time by CDF in 2005 in 180 pb^{-1} of integrated luminosity: 8 events have been counted, and the branching ratio (\mathcal{B}) has been measured.⁴ Recently, CDF presents an updated analysis with 2.9 fb^{-1} of data collected with the displaced track trigger.⁵ The reconstructed signal events are $295 \pm 20(\text{stat}) \pm 12(\text{syst})$ and $\mathcal{B} = [2.40 \pm 0.21(\text{stat}) \pm 0.86(\text{syst})] \times 10^{-5}$, which is consistent with the previous result and with the theoretical prediction.⁹

We report the first polarization measurement of such decays using the same data set of the branching fraction update.⁶ In this analysis, the untagged time-integrated decay rate as a function of three angular variables of the final state decay products is considered. The polarization amplitudes are corrected for the expected lifetime difference for the B_s^0 mass eigenstates using the world average B_s^0 lifetime and width difference,⁷ and the tiny CP phase in B_s^0 mixing is neglected, as expected in the SM.^{b, 7} Thus, a fit to the reconstructed B_s^0 mass and to the

^aThe three polarization amplitudes are constrained by the unitarity condition: $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$.

^bAnyway, the effect related to a possible non vanishing CP-violating phase in mixing at a level consistent with the current world average is included in the systematic treatment.

decay product angular distributions is performed. The approach is validated by performing a similar measurement using $B_s^0 \rightarrow J/\psi\phi$ decays, collected via the same trigger, and comparing the obtained results with the current experimental information on the polarization in such a decay.⁸ The measured polarization amplitudes and the cosine of $\delta_{\parallel} = \arg(A_0^* A_{\parallel})$ are: $|A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst})$, $|A_{\parallel}|^2 = 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst})$, $|A_{\perp}|^2 = 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst})$ and $\cos \delta_{\parallel} = -0.91_{-0.13}^{+0.15}(\text{stat}) \pm 0.09(\text{syst})$. This measurement indicates that the expected amplitudes hierarchy is disfavored in this charmless B_s^0 decay, being $|A_0|^2 < |A_{\parallel}|^2 + |A_{\perp}|^2$. The plot in Fig. 1 (a) shows the estimates point for $f_0 = |A_0|^2$ versus $f_{\parallel} = |A_{\parallel}|^2$ compared with the prediction of different theoretical models developed in the SM.^{9,10}

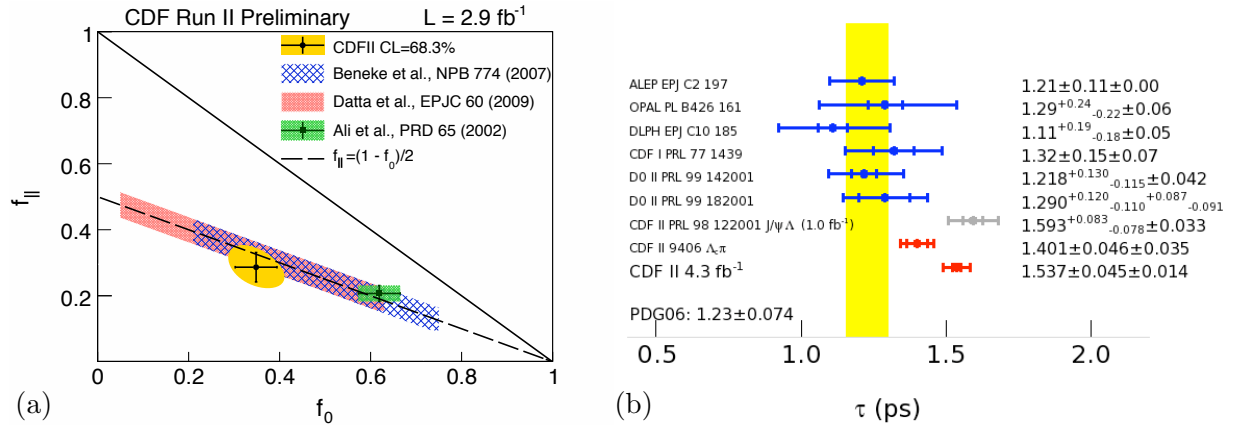


Figure 1: (a) Comparison between the $B_s^0 \rightarrow \phi\phi$ polarization measurement and several theoretical predictions. (b) Λ_b^0 lifetime: comparison between the new result and selected previous measurements.

2 Lifetimes

The lifetime of the ground state hadrons containing a b quark and lighter quarks is largely determined by the charged weak decay of the b quark. Ignoring the lighter quarks in the hadron, the spectator model predicts equal lifetimes for all b -hadrons. However, several effects change these expectations by up to about 10%. The lifetime ratio $\tau(B^+)/\tau(B^0)$ is predicted to be in the range 1.04–1.08;¹¹ for the $\tau(\Lambda_b^0)/\tau(B^0)$ the range is wider, from 0.83 to 0.93.¹²

Using a 4.3 fb⁻¹ data sample, CDF searches for fully reconstructed b -hadron decays with a J/ψ decaying to muon pairs: $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^{0*}$, $B^0 \rightarrow J/\psi K_S^0$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$.¹³ The data are collected by the dimuon trigger, which has no biasing effects on the observed proper time distribution. The analysis consists of a maximum likelihood fit to the mass, the proper decay time and the proper decay time uncertainty of the reconstructed candidates. The measured lifetimes are reported in Tab. 1: they are the most precise determination of the B^+ , B^0 and Λ_b^0 lifetimes. Several systematic uncertainties have been studied with Monte Carlo samples; while the overall systematic uncertainties remain small, the uncertainty on the extracted lifetime values is dominated by the silicon detector alignment uncertainty in the case of B mesons and by the resolution effects in the case of the Λ_b^0 . A cancellation of some common systematic uncertainties in the lifetime ratios is achieved by using the vertex of the two tracks from the J/ψ , common to all decay modes, as an estimate of the transverse decay length.^c

The Λ_b^0 lifetimes measurement has particular interest (see Fig. 1 (b)): until 2006 all measurements were in agreement and lay at the lower end of the theoretically expected value. Then,

^cThe transverse decay length is the projection of the decay length in the plane transverse to the beam.

CDF performed two high precision measurements¹⁴ which are significantly above previous results; this is confirmed by the latest result here reported.

Table 1: Lifetime measurements of b -hadrons.

Hadron	Lifetime [ps]	Lifetime ratio (over $\tau(B^0)$)	PDG 08 [ps]
B^+	$1.639 \pm 0.009(\text{stat}) \pm 0.009(\text{syst})$	$1.088 \pm 0.009(\text{stat}) \pm 0.004(\text{syst})$	1.638 ± 0.011
B^0	$1.507 \pm 0.010(\text{stat}) \pm 0.008(\text{syst})$	1	1.530 ± 0.009
Λ_b^0	$1.537 \pm 0.045(\text{stat}) \pm 0.014(\text{syst})$	$1.020 \pm 0.030(\text{stat}) \pm 0.008(\text{syst})$	$1.383^{+0.049}_{-0.048}$

3 $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ resonance structure

Since CDF has recently observed the resonant structure in the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ l^- \nu$ decay mode,¹⁵ a similar resonance structure is expected in the corresponding hadronic decay mode $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$, where the $l^- \nu$ pair is replaced by a ud quarks pair.

Last year CDF performed an analysis aimed at the first observation of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and of the following intermediate resonant states: $\Lambda_c(2595)^+ \pi^-$, $\Lambda_c(2625)^+ \pi^-$, $\Sigma_c(2455)^{++} \pi^- \pi^-$ and $\Sigma_c(2455)^0 \pi^+ \pi^-$. The analysis uses an integrated luminosity of 2.4 fb^{-1} of data collected by the CDF trigger on two displaced tracks. The Λ_c^+ is reconstructed in the $pK^- \pi^+$ decay mode and three tracks, assumed to be pions, are added to reconstruct the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$. The relative branching fractions of the resonant states to the total (\mathcal{B}_{rel}) are measured using the yields of each decay mode estimated by fitting the data mass distributions. The final results are listed in Tab. 2.

Table 2: $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ resonance structure: yields and branching fractions.

Λ_b^0 decay mode	Yield	\mathcal{B}_{rel} in 10^{-2}
$\Lambda_b^0 \rightarrow \Lambda_c(2595)^+ \pi^-$	$46.6 \pm 9.7(\text{stat})$	$2.5 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$
$\Lambda_b^0 \rightarrow \Lambda_c(2625)^+ \pi^-$	$114 \pm 13(\text{stat})$	$6.2 \pm 1.0(\text{stat})^{+1.0}_{-0.9}(\text{syst})$
$\Lambda_b^0 \rightarrow \Sigma_c(2455)^{++} \pi^- \pi^-$	$81 \pm 15(\text{stat})$	$5.2 \pm 1.1(\text{stat}) \pm 0.8(\text{syst})$
$\Lambda_b^0 \rightarrow \Sigma_c(2455)^0 \pi^+ \pi^-$	$41.5 \pm 9.3(\text{stat})$	$8.9 \pm 2.1(\text{stat})^{+1.2}_{-1.0}(\text{syst})$

4 Masses: the Ω_b^- observation

The quark model predicts a rich spectrum of baryons containing b quarks.¹⁷ In 2007, the accumulation of large data sets from the Tevatron allowed the first observation of new baryons, the Ξ_b^- and the $\Sigma_b^{(*)-}$.^{18,19} The Ω_b^- is the latest observed of such heavy states: in 2008, DØ made its discovery using 1.3 fb^{-1} of data,²⁰ while CDF observed it last year in 4.2 fb^{-1} .²¹ In both cases, the Ω_b^- observation is made through the decay chain $\Omega_b^- \rightarrow J/\psi \Omega^-$, where $J/\psi \rightarrow \mu^+ \mu^-$, $\Omega^- \rightarrow \Lambda K^-$, and $\Lambda \rightarrow p \pi^-$.^d However, the two experiments measure a Ω_b^- mass in significant disagreement. The DØ analysis is built on the Ξ_b^- discovery;¹⁸ a yield of $17.8 \pm 4.9(\text{stat}) \pm 0.8(\text{syst})$ Ω_b^- events is extracted, with a significance of 5.4 Gaussian standard deviations that the observed peak is not due to background fluctuations. The estimated Ω_b^- mass is $6165 \pm 10(\text{stat}) \pm 13(\text{syst}) \text{ MeV}/c^2$.

In the Ω_b^- observation, in addition to its mass, CDF measures for the first time its lifetime. Moreover, in the same analysis, CDF updates the Ξ_b^- mass measurement and performs its first lifetime measurement.^e CDF measures the Ω_b^- mass, $m = 6054.4 \pm 6.8(\text{stat}) \pm 0.9(\text{syst}) \text{ MeV}/c^2$, and lifetime, $\tau = 1.13^{+0.53}_{-0.40}(\text{stat}) \pm 0.02(\text{syst}) \text{ ps}$, using a signal of $16^{+6}_{-4}(\text{stat})$ (5.5σ significance),

^dCharge conjugate modes are included implicitly.

^eUsing the decay chain $\Xi_b^- \rightarrow J/\psi \Xi^-$, where $J/\psi \rightarrow \mu^+ \mu^-$, $\Xi^- \rightarrow \Lambda \pi^-$, and $\Lambda \rightarrow p \pi^-$.

and the Ξ_b^- mass, $m = 5790.9 \pm 2.6(\text{stat}) \pm 0.8(\text{syst}) \text{ MeV}/c^2$, and lifetime, $\tau = 1.56^{+0.27}_{-0.25}(\text{stat}) \pm 0.02(\text{syst}) \text{ ps}$. The small systematic uncertainties in the CDF measurements are due to the ability to reconstruct the actual trajectory of the long-lived hyperons from their hits in the silicon tracker.

The disagreement between the CDF and DØ Ω_b^- mass measurements consists of about six standard deviations. In addition, the measured Ω_b^- production rates relative to the Ξ_b are different between the two experiments, being $f_{\text{CDF}} = 0.27 \pm 0.12(\text{stat}) \pm 0.01(\text{syst})$ and $f_{\text{DØ}} = 0.80 \pm 0.32(\text{stat})^{+0.14}_{-0.22}(\text{syst})$. Neither measurement is very precise; nevertheless, CDF indicates a rate substantially lower than DØ. The mass obtained by CDF agrees with theoretical estimates.¹⁷ Clearly, further studies are needed to resolve the discrepancies and analysis updates are ongoing with the addition of new available data.

5 Conclusions

In the latest years, the CDF and DØ heavy flavor programs reached maturation, yielding results that are competitive to the B factories ones for the B^\pm and B^0 properties measurement, and complementary to them for the study of the b -baryons and the B_s^0 meson. We presented here a small sampling of recent results, including the first measurement of decay-polarization structure in a charmless B_s^0 decay, world-leading measurements of b -hadron lifetimes, the structure study of a Λ_b^0 hadronic decay mode and the observation of the Ω_b^- baryon. These are obtained using just a fraction of the presently available data-samples, which keep increasing at a pace of 70 pb^{-1} per week. The large amount of data, and ever improving analysis technique suggest a few years of exciting competition with the LHCb experiment that has just started its operations.

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